

Neutrino fluxes and anomalies from nuclear reactors

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Neutrino Seminar

April 23, 2015, Fermi National Accelerator Laboratory

Why care?

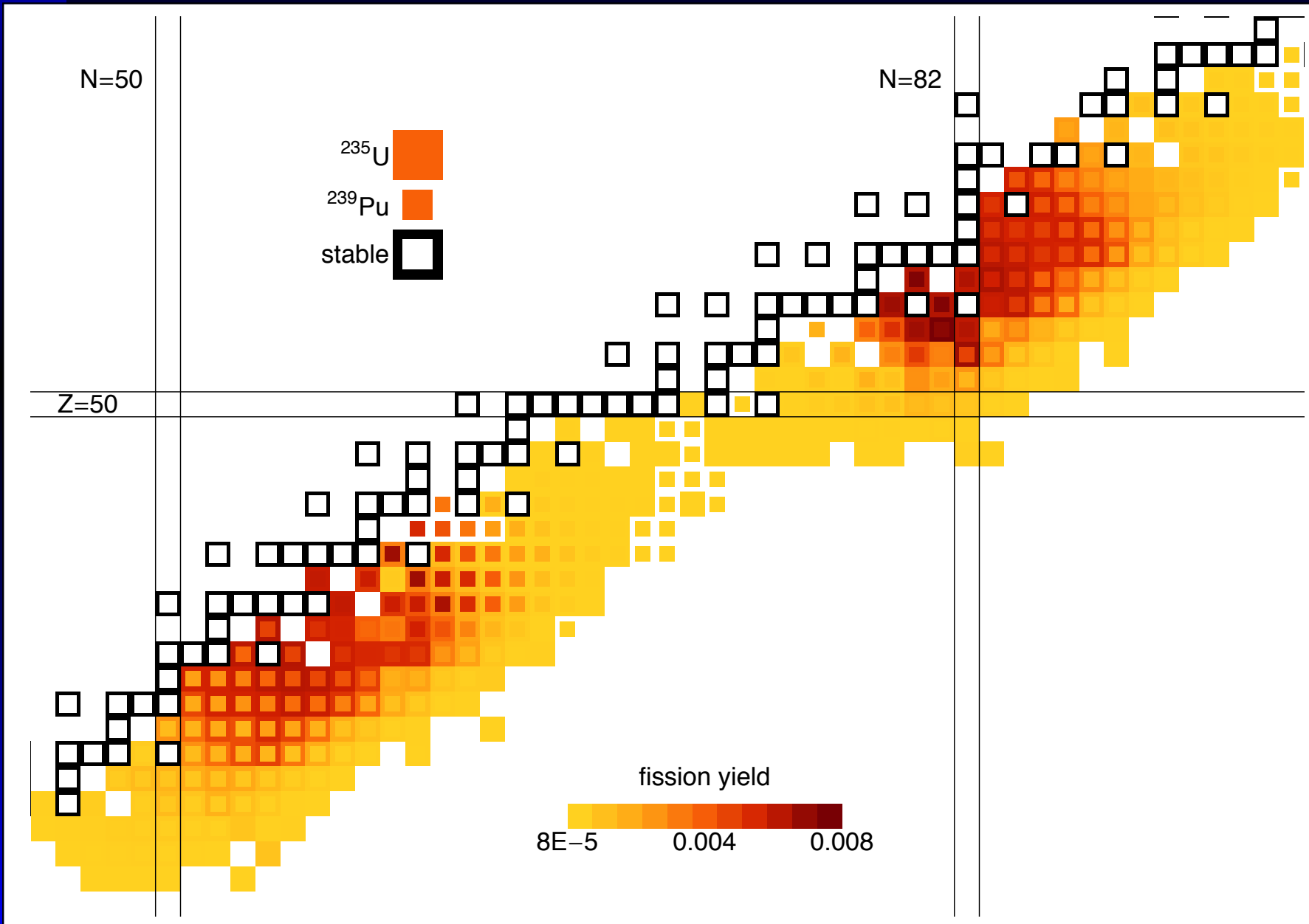
Antineutrinos from reactors have been the workhorse of neutrino physics since the discovery of the neutrino at Savannah River.

Recent results indicate a net increase in **predicted** flux, which in turn implies a deficit in **observed** flux – this mismatch is known as the Reactor Antineutrino Anomaly (RAA) and could imply the existence of a sterile neutrino around 1 eV mass.

As result there are about a dozen or so experiments proposed to study reactor antineutrinos at very close range to reactors.

For potential safeguards applications a precise understanding of the antineutrino yields from different fissile isotopes is essential.

Fission yields of β emitters



Neutrinos from fission



with average masses of X_1 of about $A=94$ and X_2 of about $A=140$. X_1 and X_2 have together 142 neutrons.

The stable nuclei with $A=94$ and $A=140$ are $^{94}_{40}\text{Zr}$ and $^{140}_{58}\text{Ce}$, which together have only 136 neutrons.

Thus 6 β -decays will occur, yielding 6 $\bar{\nu}_e$. About 2 will be above inverse β -decay threshold.

How does one compute the number and spectrum of neutrinos above inverse β -decay threshold?

Beta decay theory

In Fermi theory, the spectrum of massless neutrinos is obtained from

$$E_\nu = E_0 - E_e$$

In reality there are many corrections: finite nuclear size, radiative corrections, screening effects, induced currents, ... which in principle can be computed for allowed decays but **not** for forbidden ones.

There is a sizable fraction of around 40% of all neutrinos coming from forbidden decays, essentially for reasons of combinatorics.

β -decay – Fermi theory

$$N_\beta(W) = K \underbrace{p^2(W - W_0)^2}_{\text{phase space}} F(Z, W),$$

where $W = E/(m_e c^2) + 1$ and W_0 is the value of W at the endpoint. K is a normalization constant.

$F(Z, W)$ is the so called Fermi function and given by

$$F(Z, W) = 2(\gamma + 1)(2pR)^{2(\gamma-1)} e^{\pi\alpha ZW/p} \frac{|\Gamma(\gamma + i\alpha ZW/p)|^2}{\Gamma(2\gamma + 1)^2}$$

$$\gamma = \sqrt{1 - (\alpha Z)^2}$$

The Fermi function is the modulus square of the electron wave function at the origin.

Corrections to Fermi theory

$$N_{\beta}(W) = K p^2 (W - W_0)^2 F(Z, W) L_0(Z, W) C(Z, W) S(Z, W) \\ \times G_{\beta}(Z, W) (1 + \delta_{\text{WM}} W) .$$

The neutrino spectrum is obtained by the replacements $W \rightarrow W_0 - W$ and $G_{\beta} \rightarrow G_{\nu}$.

All these correction have been studied 15-30 years ago.

Weak currents

In the following we assume $q^2 \ll M_W$ and hence charged current weak interactions can be described by a current-current interaction.

$$-\frac{G_F}{\sqrt{2}} V_{ud} J_\mu^h J_\mu^l$$

where

$$J_\mu^h = \bar{\psi}_u \gamma_\mu (1 + \gamma_5) \psi_d = V_\mu^h + A_\mu^h$$

However, we are not dealing with free quarks ...

Induced currents

Describe protons and neutrons as spinors which are solutions to the free Dirac equation, but which are **not** point-like, we obtain for the hadronic current

$$V_\mu^h = i\bar{\psi}_p \left[g_V(q^2)\gamma_\mu + \frac{g_M(q^2)}{8M}\sigma_{\mu\nu}q_\nu + ig_S(q^2)q_\mu \right] \psi_n$$

$$A_\mu^h = i\bar{\psi}_p \left[g_A(q^2)\gamma_\mu\gamma_5 + \frac{g_T(q^2)}{8M}\sigma_{\mu\nu}q_\nu\gamma_5 + ig_P(q^2)q_\mu\gamma_5 \right] \psi_n$$

In the limit $q^2 \rightarrow 0$ the form factors $g_X(q^2) \rightarrow g_X$, *i.e.* new induced couplings, which are not present in the SM Lagrangian, but are induced by the bound state QCD dynamics. Note, that some form factors are absent in the SM.

Weak magnetism & β -spectra

g_M is call weak magnetism and the question is how it manifests itself in nuclear β -decay. Nuclear structure effects can be summarized by the use of appropriate form factors F_X^N .

The weak magnetic nuclear, F_M^N form factor by virtue of CVC is given in terms of the analog EM form factor as

$$F_M^N(0) = \sqrt{2}\mu(0)$$

The effect on the β decay spectrum is given by

$$1 + \delta_{WM}W \simeq 1 + \frac{4}{3M} \frac{F_M^N(0)}{F_A^N(0)} W$$

Impulse approximation

In the impulse approximation nuclear β -decay is described as the decay of a free nucleon inside the nucleus. The sole effect of the nucleus is to modify the initial and final state densities.

In impulse approximation

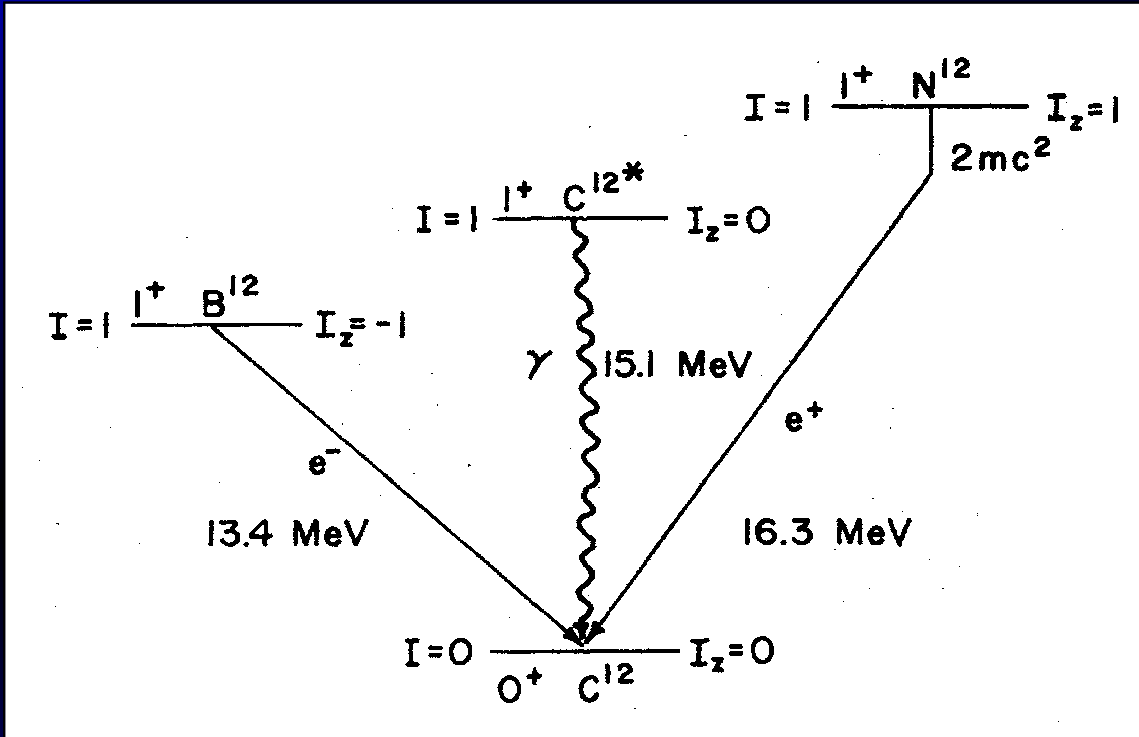
$$F_M^N(0) = \mu_p - \mu_n \simeq 4.7 \quad \text{and} \quad F_A^N(0) = C_A \simeq 1.27,$$

and thus

$$\delta_{WM} \simeq 0.5\% \text{ MeV}^{-1}$$

This value, in impulse approximation, is universal for all β -decays since it relies only on free nucleon parameters.

Isospin analog γ -decays



$$\Gamma(C^{12*} \rightarrow C^{12})_{M1} = \frac{\alpha E_\gamma^3}{3M^2} \left| \sqrt{2}\mu(0) \right|^2$$

$$b := \sqrt{2}\mu(0) = F_M^N(0)$$

B. Holstein, Rev. Mod. Phys. **46**, 789, 1974.

Gamow-Teller matrix element c

$$c = F_A^N(0) = \sqrt{\frac{2ft_{\text{Fermi}}}{ft}}$$

and thanks to CVC $ft_{\text{Fermi}} \simeq 3080 \text{ s}$ is universal

What is the value of δ_{WM} ?

Three ways to determine δ_{WM}

- impulse approximation – universal value $0.5\% \text{ MeV}^{-1}$
- using CVC – F_M from analog M1 γ -decay width, F_A from ft value
- direct measurement in β -spectrum – only very few, light nuclei have been studied. In those cases the CVC predictions are confirmed within (sizable) errors.

In the following, we will compare the results from CVC with the ones from the impulse approximation.

CVC at work

Collect all nuclei for which we

- can identify the isospin analog energy level
- and know Γ_{M1}

then, compute the resulting δ_{WM} . This exercise has been done in Calaprice, Holstein, Nucl. Phys. **A273** (1976) 301. and they find for nuclei with $ft < 10^6$

$$\delta_{WM} = 0.82 \pm 0.4\% \text{ MeV}^{-1}$$

which is in reasonable agreement with the impulse approximated value of $\delta_{WM} = 0.5\% \text{ MeV}^{-1}$. Our result for $ft < 10^6$ is $\delta_{WM} = (0.67 \pm 0.26) \% \text{ MeV}^{-1}$.

CVC at work

Decay	$J_i \rightarrow J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ / Ac	$ dN/dE $ (% MeV ⁻¹)
${}^6\text{He} \rightarrow {}^6\text{Li}$	$0^+ \rightarrow 1^+$	3563	8.2	71.8	805.2	2.76	4.33	0.646
${}^{12}\text{B} \rightarrow {}^{12}\text{C}$	$1^+ \rightarrow 0^+$	15110	43.6	37.9	11640.	0.726	4.35	0.62
${}^{12}\text{N} \rightarrow {}^{12}\text{C}$	$1^+ \rightarrow 0^+$	15110	43.6	37.9	13120.	0.684	4.62	0.6
${}^{18}\text{Ne} \rightarrow {}^{18}\text{F}$	$0^+ \rightarrow 1^+$	1042	0.258	242.	1233.	2.23	6.02	0.8
${}^{20}\text{F} \rightarrow {}^{20}\text{Ne}$	$2^+ \rightarrow 2^+$	8640	4.26	45.7	93260.	0.257	8.9	1.23
${}^{22}\text{Mg} \rightarrow {}^{22}\text{Na}$	$0^+ \rightarrow 1^+$	74	0.0000233	148.	4365.	1.19	5.67	0.757
${}^{24}\text{Al} \rightarrow {}^{24}\text{Mg}$	$4^+ \rightarrow 4^+$	1077	0.046	129.	8511.	0.85	6.35	0.85
${}^{26}\text{Si} \rightarrow {}^{26}\text{Al}$	$0^+ \rightarrow 1^+$	829	0.018	130.	3548.	1.32	3.79	0.503
${}^{28}\text{Al} \rightarrow {}^{28}\text{Si}$	$3^+ \rightarrow 2^+$	7537	0.3	20.8	73280.	0.29	2.57	0.362
${}^{28}\text{P} \rightarrow {}^{28}\text{Si}$	$3^+ \rightarrow 2^+$	7537	0.3	20.8	70790.	0.295	2.53	0.331
${}^{14}\text{C} \rightarrow {}^{14}\text{N}$	$0^+ \rightarrow 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6
${}^{14}\text{O} \rightarrow {}^{14}\text{N}$	$0^+ \rightarrow 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92
${}^{32}\text{P} \rightarrow {}^{32}\text{S}$	$1^+ \rightarrow 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9

None of this is anywhere close to A=90...

What happens for large ft ?

Decay	$J_i \rightarrow J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ / Ac	$ dN/dE $ (% MeV ⁻¹)
$^{14}\text{C} \rightarrow ^{14}\text{N}$	$0^+ \rightarrow 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6
$^{14}\text{O} \rightarrow ^{14}\text{N}$	$0^+ \rightarrow 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92
$^{32}\text{P} \rightarrow ^{32}\text{S}$	$1^+ \rightarrow 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9

Including these large ft nuclei, we have

$$\delta_{WM} = (4.78 \pm 10.5) \% \text{ MeV}^{-1}$$

which is about 10 times the impulse approximated value and this are about 3 nuclei out of 10-20...

NB, a shift of δ_{WM} by $1\% \text{ MeV}^{-1}$ shifts the total neutrino flux above inverse β -decay threshold by $\sim 2\%$.

Neutrinos from fission

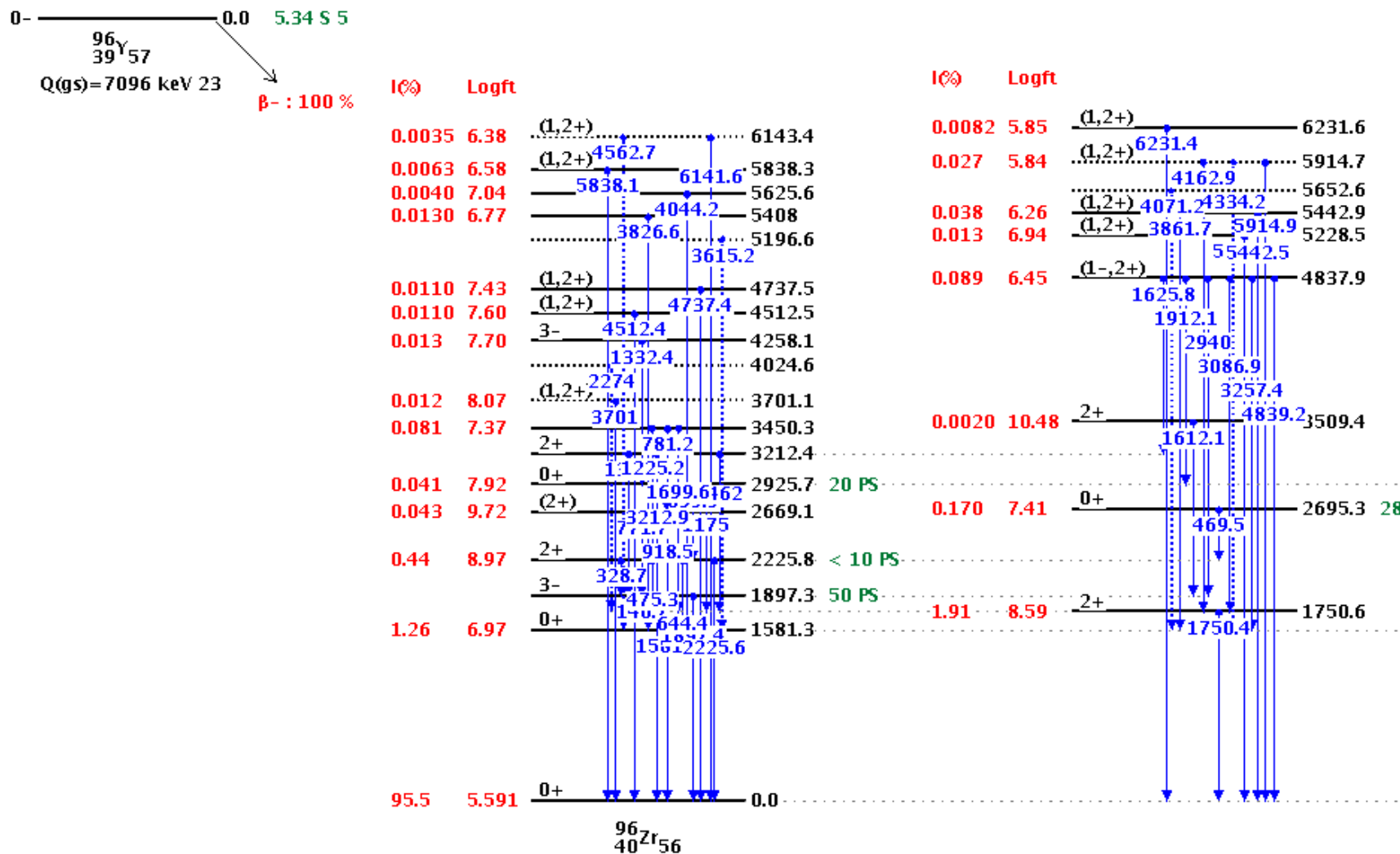
For a single branch energy conservation implies a one-to-one correspondence between β and $\bar{\nu}$ spectrum.

However, here there are about 500 nuclei and 10 000 individual β -branches involved; many are far away from stability.

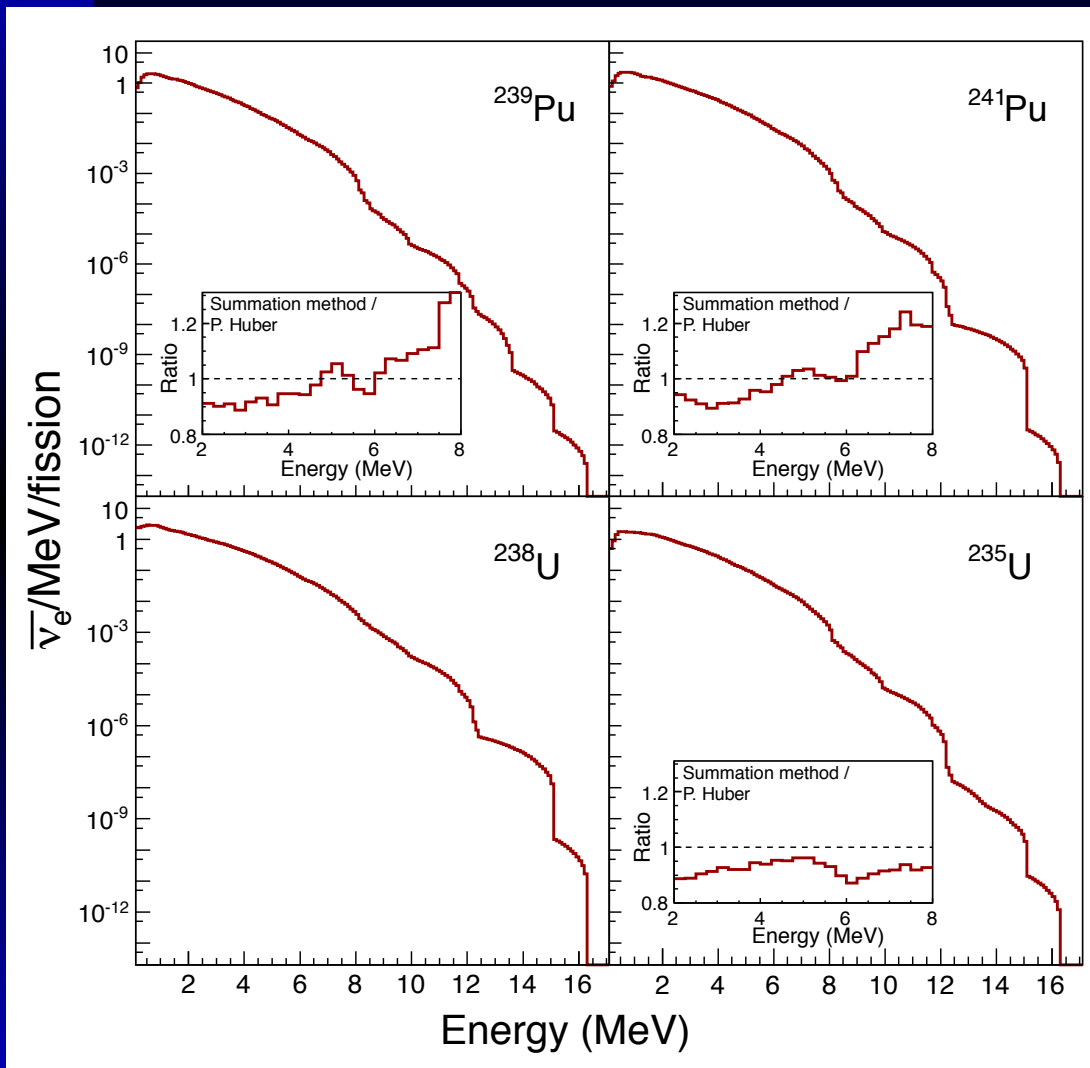
Direct β spectroscopy of single nuclei never will be complete, and even then one has to untangle the various branches

γ spectroscopy yields energy levels and branching fractions, but with limitations, *cf.* pandemonium effect

β branches



A priori calculations



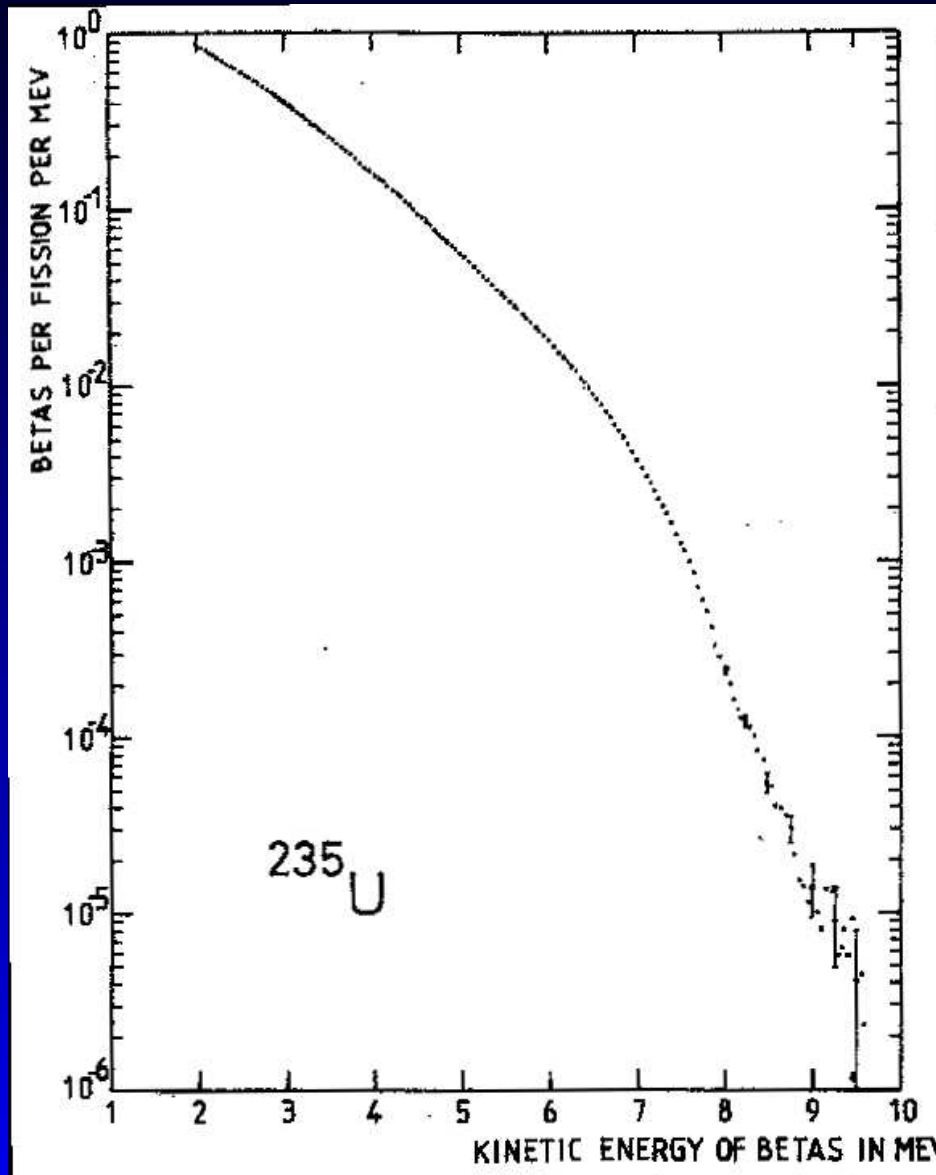
Updated β -feeding functions from total absorption γ spectroscopy (safe from pandemonium) for the isotopes: $^{102,104,105,106,107}\text{Tc}$, ^{105}Mo and ^{102}Nb

The calculation for ^{238}U agrees within 10% with measurement of Haag *et al.*

Still a 10-20% discrepancy with the measured total β -spectra.

Fallot *et al.*, 2012

β -spectrum from fission



^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

For ^{238}U recent measurement by Haag *et al.*, 2013

Schreckenbach, *et al.* 1985.

Extraction of ν -spectrum

The total β -spectrum is a sum of all decay branches

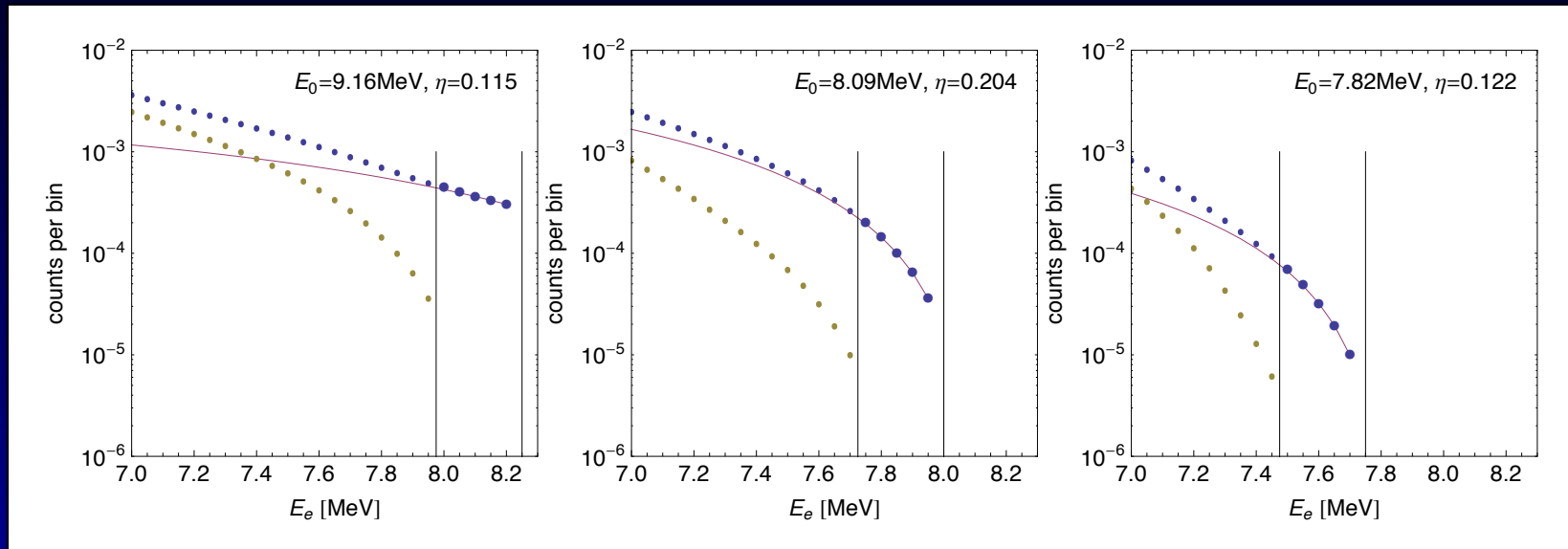
$$\mathcal{N}_\beta(E_e) = \int dE_0 N_\beta(E_e, E_0; \bar{Z}) \eta(E_0) .$$

with \bar{Z} effective nuclear charge and $\eta(E_0)$, the underlying distribution of endpoints

This is a so called Fredholm integral equation of the first kind – mathematically ill-posed, *i.e.* solutions tend to oscillate, needs regulator.

This approach is the basis for “virtual branches” Schreckenbach *et al.*, 1982, 1985, 1989 and is used in the modern calculations as well Mueller *et al.* 2011, Huber 2011

Virtual branches



1 – fit an allowed β -spectrum with free normalization η and endpoint energy E_0 the last s data points

2 – delete the last s data points

3 – subtract the fitted spectrum from the data

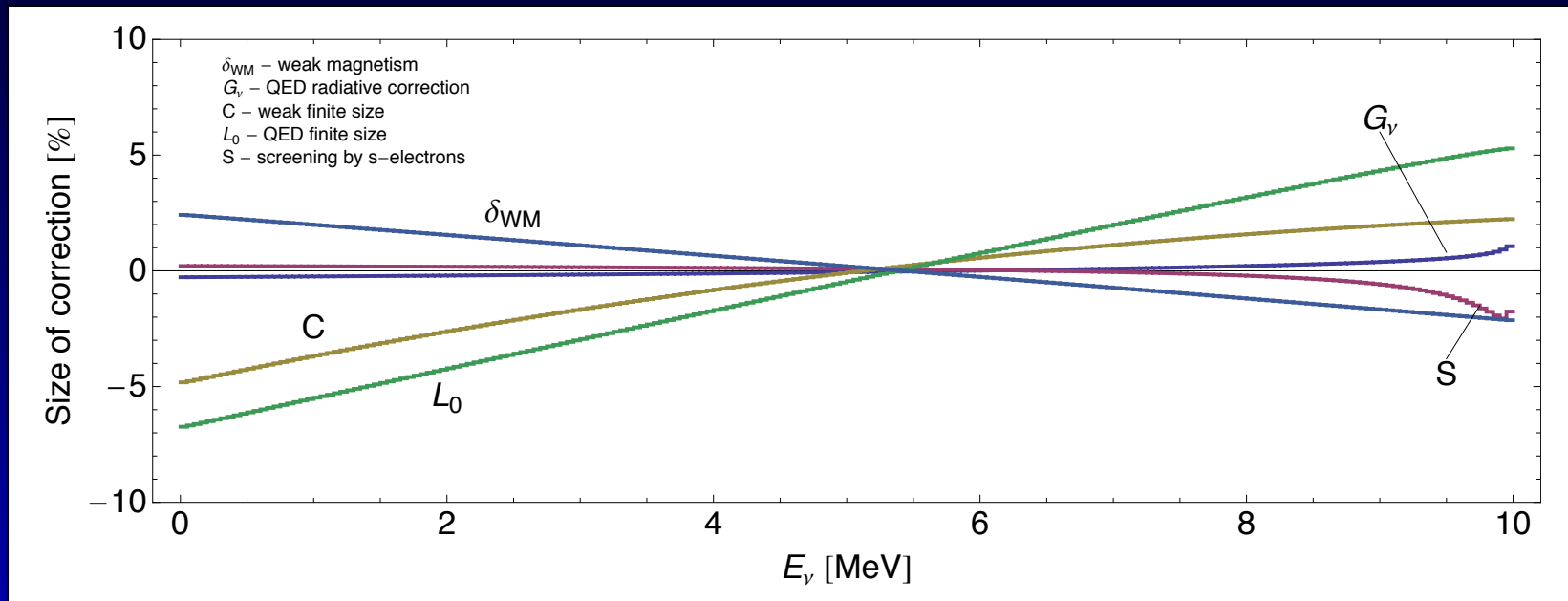
4 – goto 1

Invert each virtual branch using energy conservation into a neutrino spectrum and add them all.

e.g. Vogel, 2007

Corrections to β -shape

There are numerous correction to the β -spectrum



Many of these correction depend on the nuclear charge Z , but Z is not determined by the β -spectrum measurement \Rightarrow nuclear databases.

Effective nuclear charge

In order to compute all the QED corrections we need to know the nuclear charge Z of the decaying nucleus.

Using virtual branches, the fit itself cannot determine Z since many choices for Z will produce an excellent fit of the β -spectrum

\Rightarrow use nuclear database to find how the average nuclear charge changes as a function of E_0 , this is what is called effective nuclear charge $\bar{Z}(E_0)$.

Weigh each nucleus by its fission yield and bin the resulting distribution in E_0 and fit a second order polynomial to it.

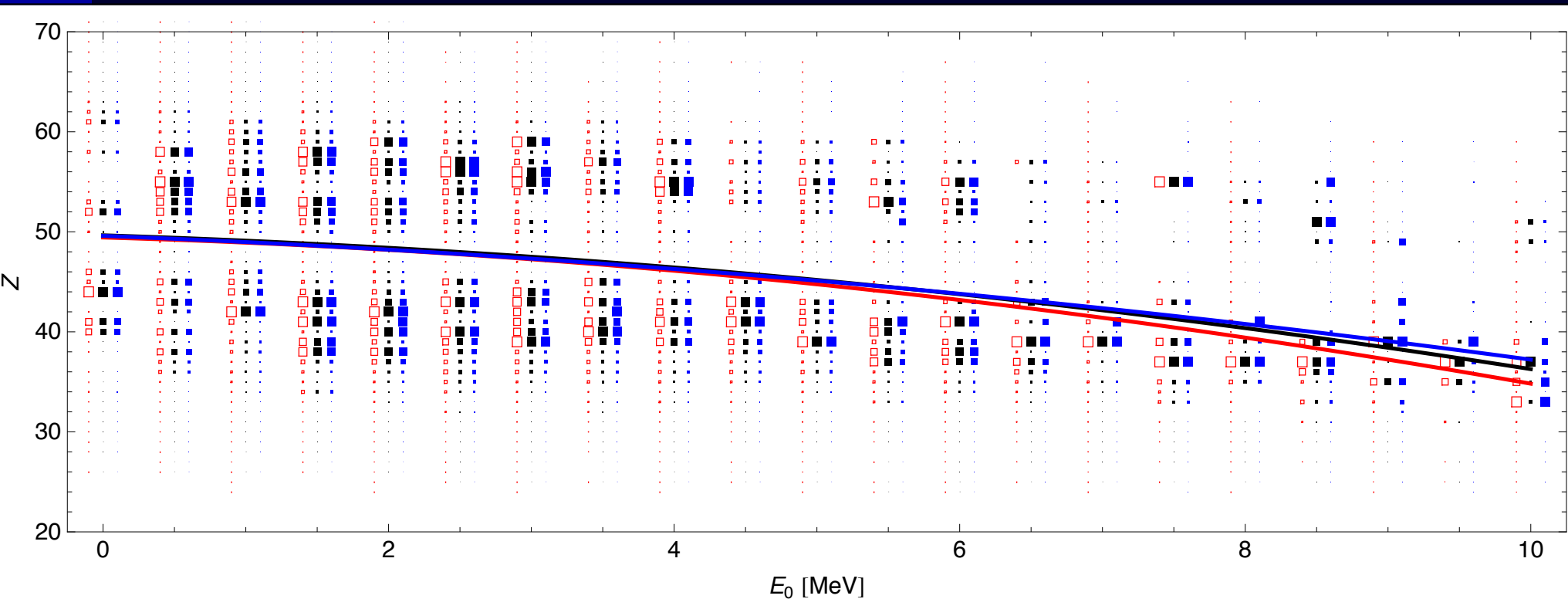
Effective nuclear charge

The nuclear databases have two fundamental shortcomings

- they are incomplete – for the most neutron-rich nuclei we only know the $Q_{gs \rightarrow gs}$, *i.e.* the mass differences
- they are incorrect – for many of the neutron-rich nuclei, γ -spectroscopy tends to overlook faint lines and thus too much weight is given to branches with large values of E_0 , aka pandemonium effect

Simulation using our synthetic data set: by removing a fraction of the most neutron-rich nuclei and/or by randomly distributing the decays of a given branch onto several branches with $0 < E_0 < Q_{gs \rightarrow gs}$.

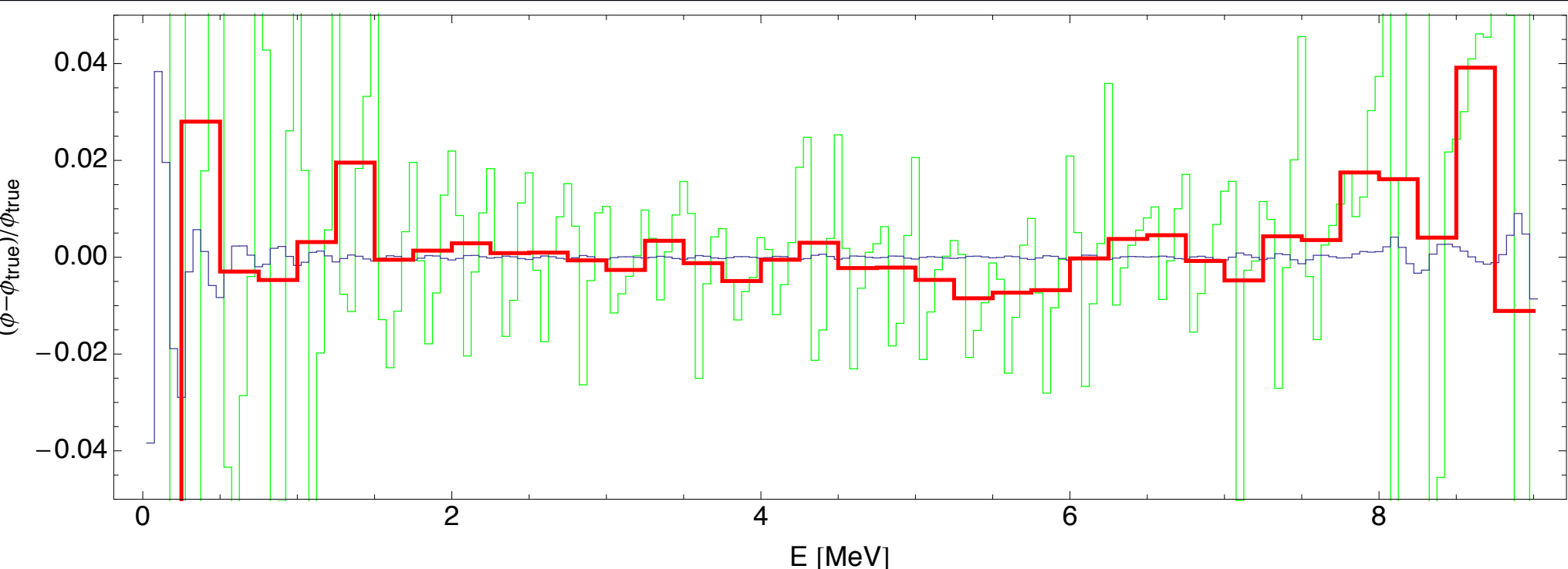
Effective nuclear charge



Spread between lines – effect of incompleteness and incorrectness of nuclear database (ENSDF). Only place in this analysis, where database enters directly.

Bias

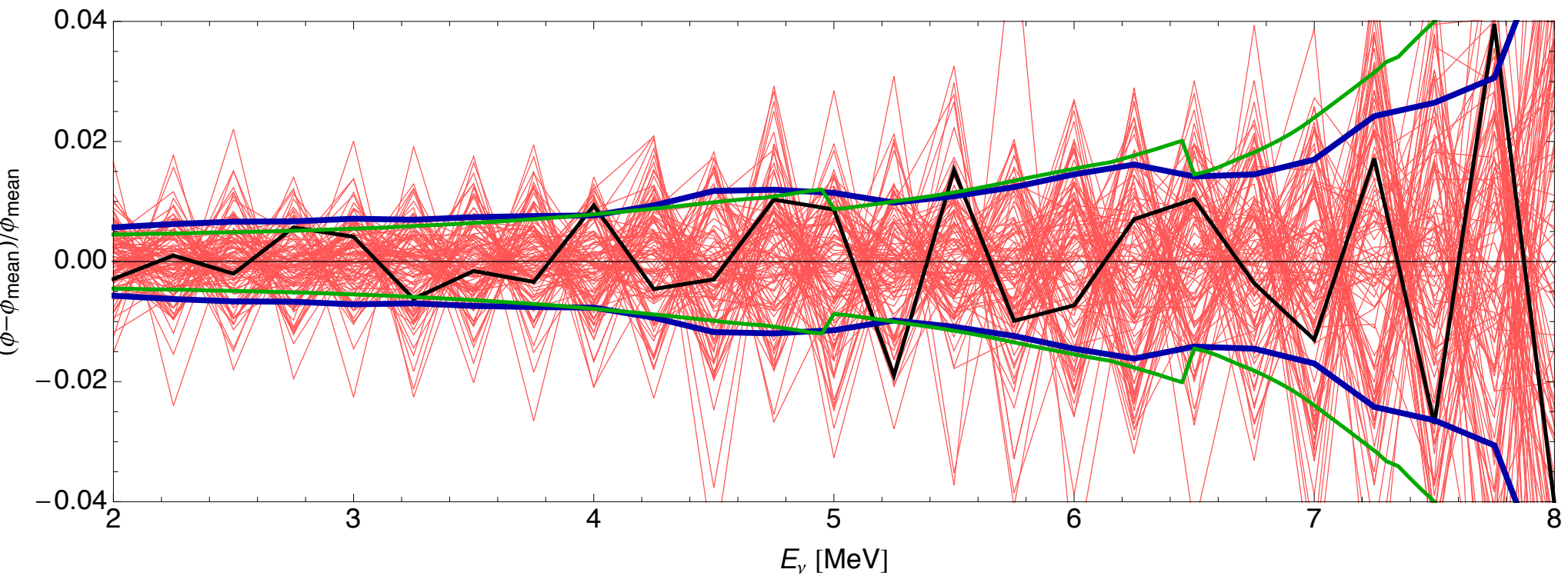
Use synthetic data sets derived from cumulative fission yields and ENSDF, which represent the real data within 10-20% and compute bias



Approximately 500 nuclei and 8000 β -branches.

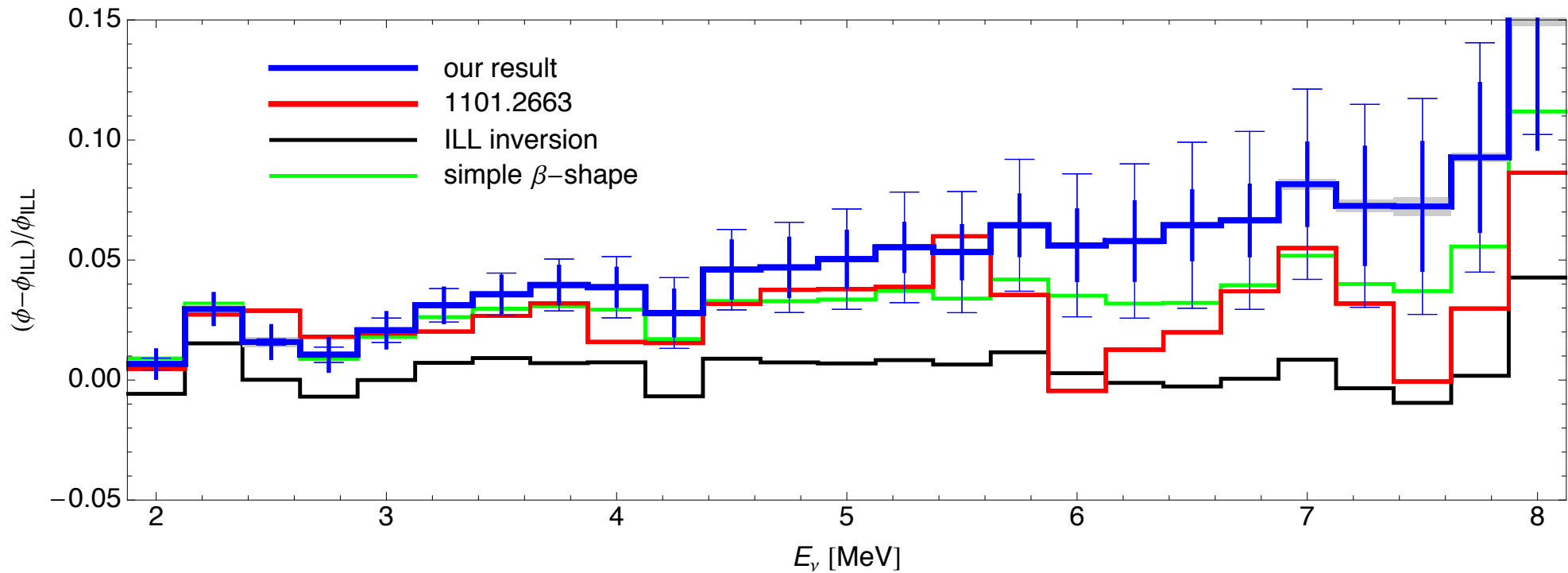
Statistical Error

Use synthetic data sets and fluctuate β -spectrum within the variance of the actual data.



Amplification of stat. errors of input data by factor 7.

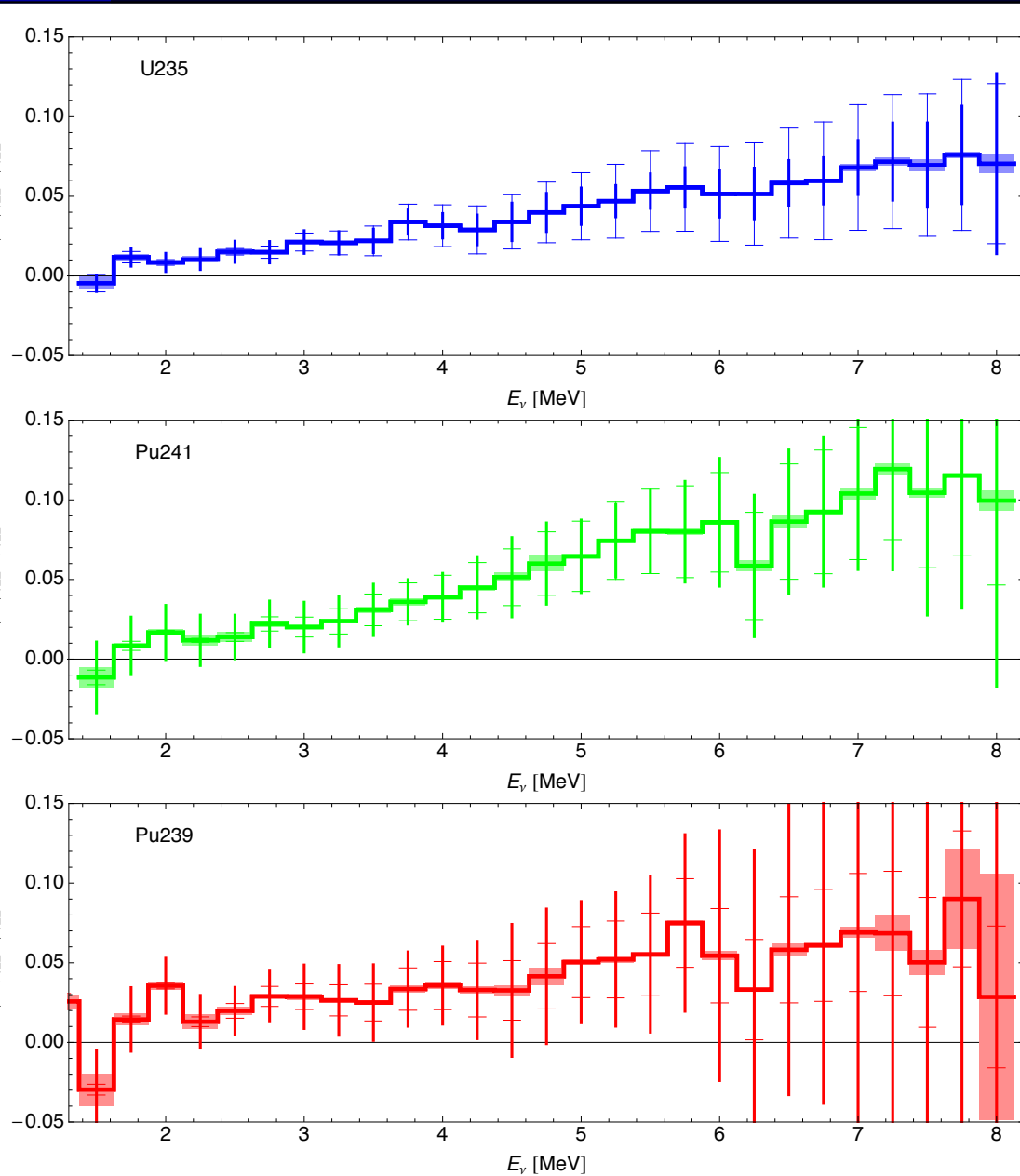
Reactor antineutrino fluxes



Shift with respect to ILL results, due to

- different effective nuclear charge distribution
- branch-by-branch application of shape corrections

Comparison of isotopes

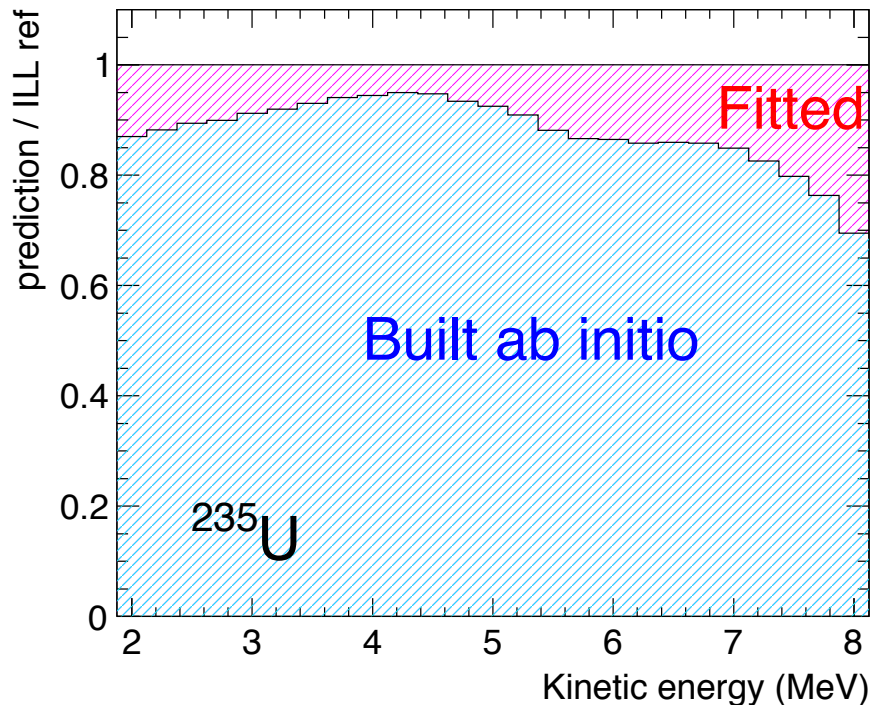


Same shift in all isotopes

Statistical errors of different size, direct consequence of different ILL data quality

^{239}Pu most problematic due to large fission fraction

From first principles?

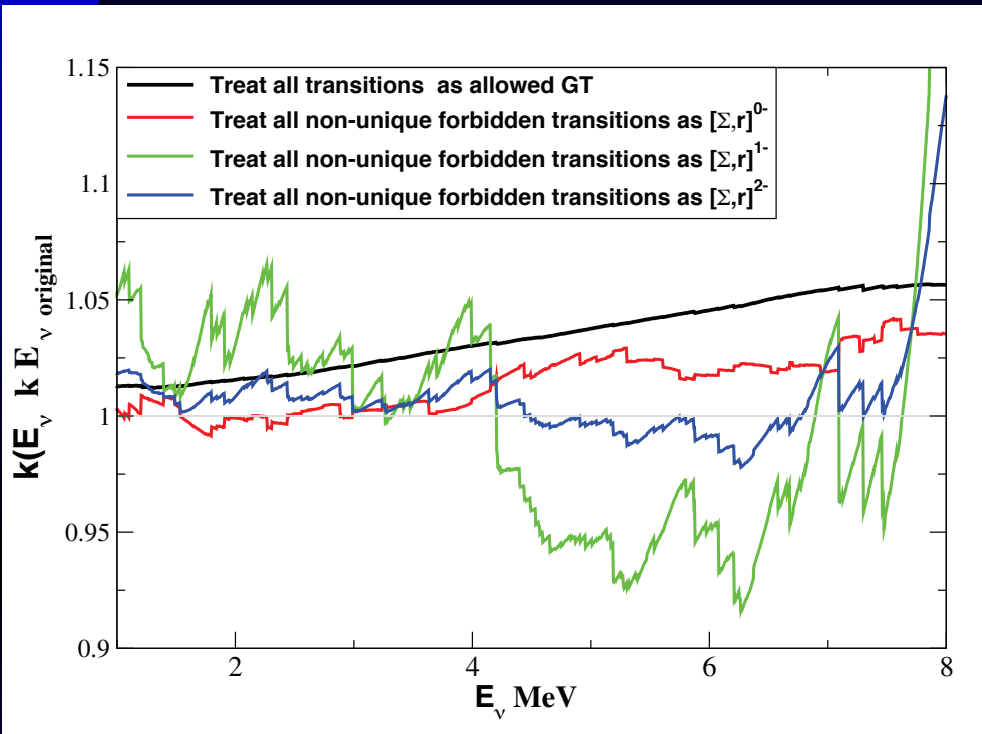


In *Mueller et al.*, *Phys.Rev.* **C83** (2011) 054615 an attempt was made to compute the neutrino spectrum from fission yields and information on individual β decay branches from databases.

The resulting cumulative β spectrum should match the ILL measurement.

About 10-15% of electrons are missing, *Mueller et al.* use virtual branches for that small remainder.

Forbidden decays



Hayes *et. al*, [arXiv:1309.4146](https://arxiv.org/abs/1309.4146) point out that in forbidden decays a mixture of different operators are involved, and that while for many of the individual operators the corrections can be computed, the relative contribution of each operator is generally unknown.

Approximate upper bound for the flux error due to forbidden decays.

Potentially large source of uncertainty.

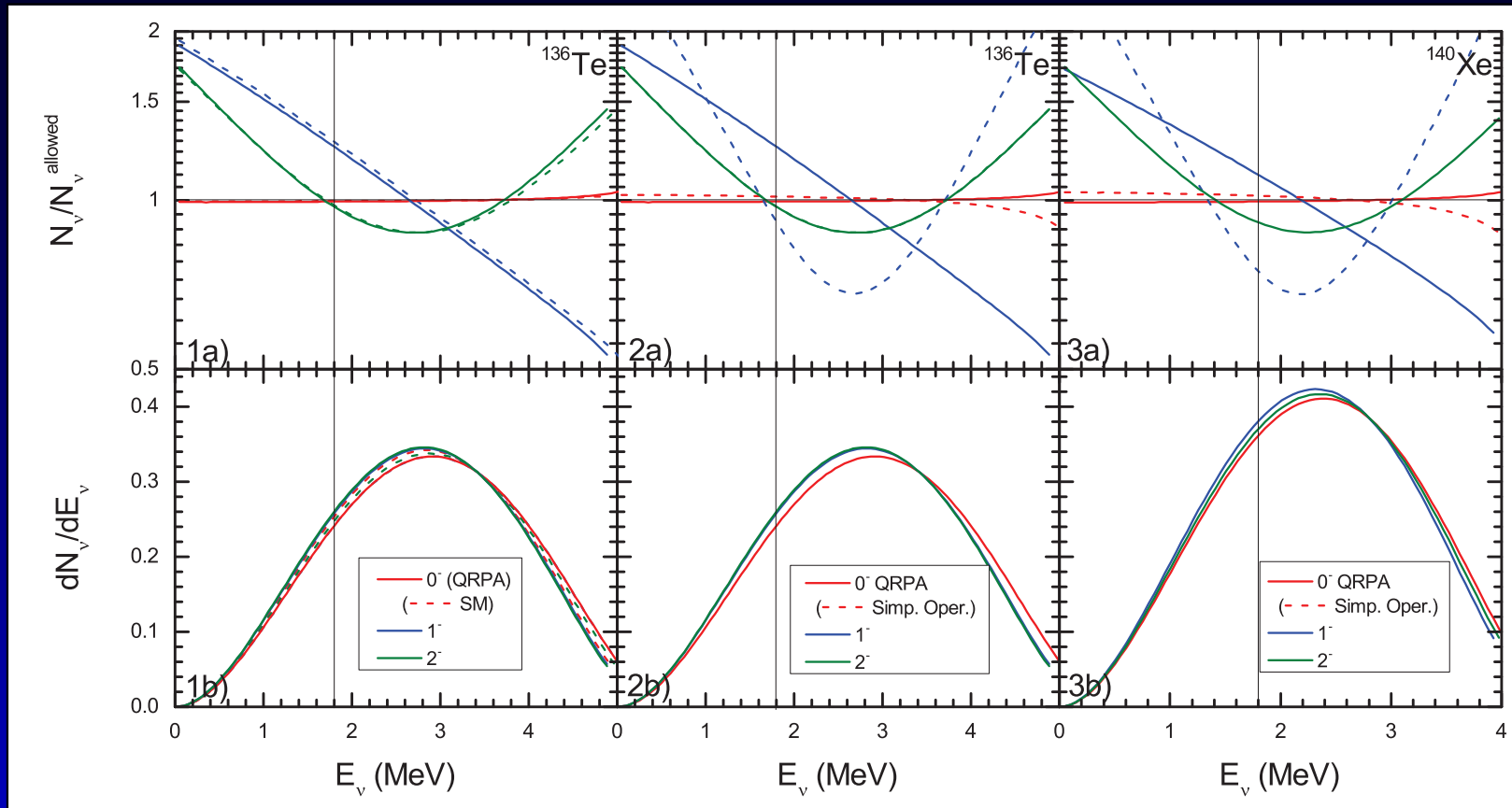
Industrial structure calculations

If we knew the nuclear wave function of parent and daughter we could compute everything we need to know.

On the other hand we do not need to compute the whole β -spectrum from scratch, we just want to know the size of certain corrections like WM. Therefore, an approximate wave function may be all that is needed.

Question: Is there a technology to perform approximate (!) calculations of nuclear wave functions which can be automatized?

Nuclear structure calculation



Fang, Brown, 2015

These are detailed calculations for the nuclei in question and indicate an overall 1-2% effect, smaller than the expansion by Hayes et al.

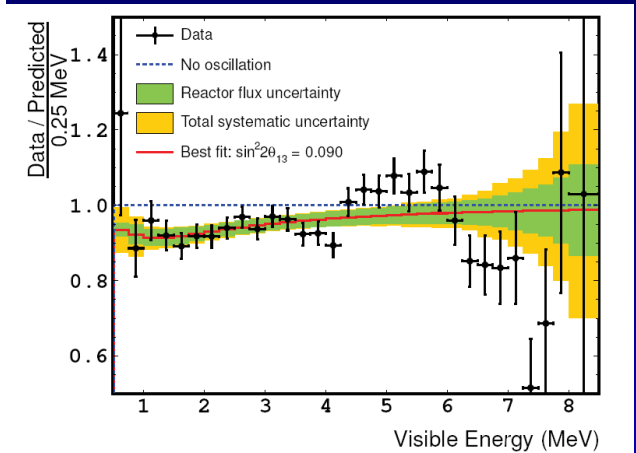
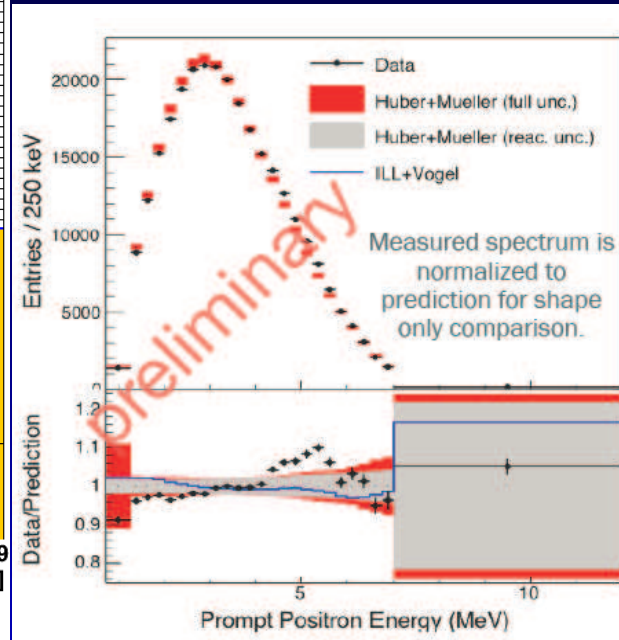
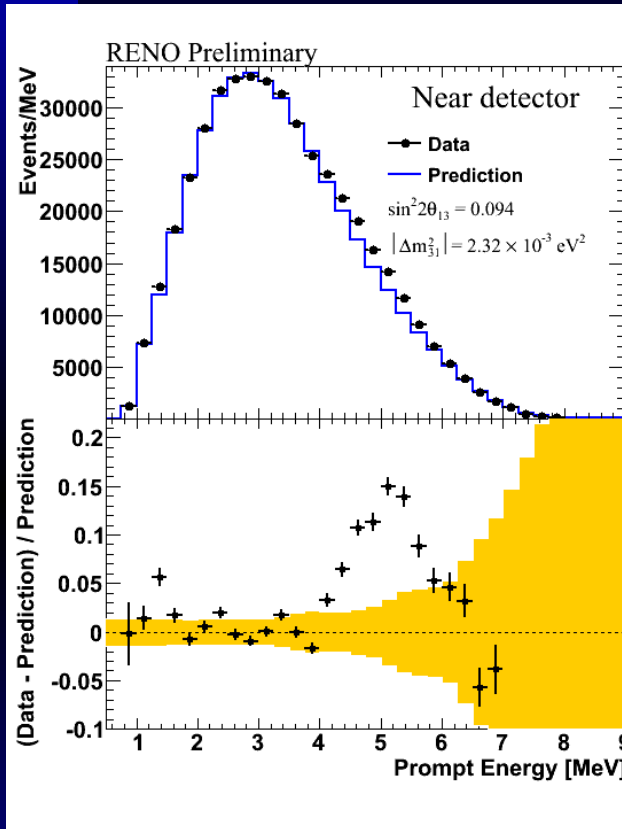
Recent neutrino measurements

In Daya Bay, RENO and Double Chooz, the distance is such that all sterile oscillations are averaged away – no confusion between nuclear physics and new physics

The statistics in the Daya Bay near detectors is around 1 million events

In combination, this should provide a good test of our ability to compute reactor fluxes

The 5 MeV bump



Seen by all three reactor experiments

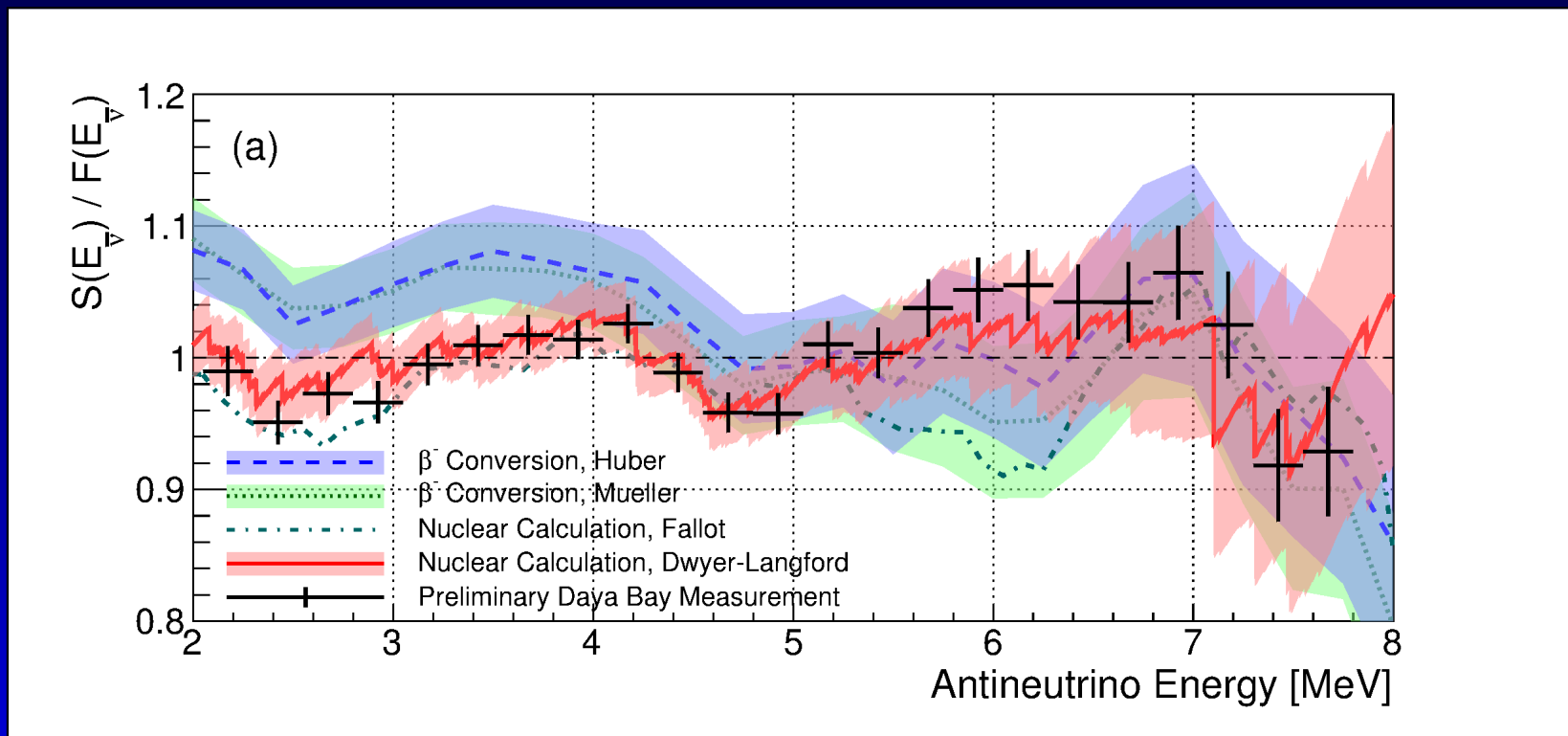
Tracks reactor power

Seems independent of burn-up

Explanations?

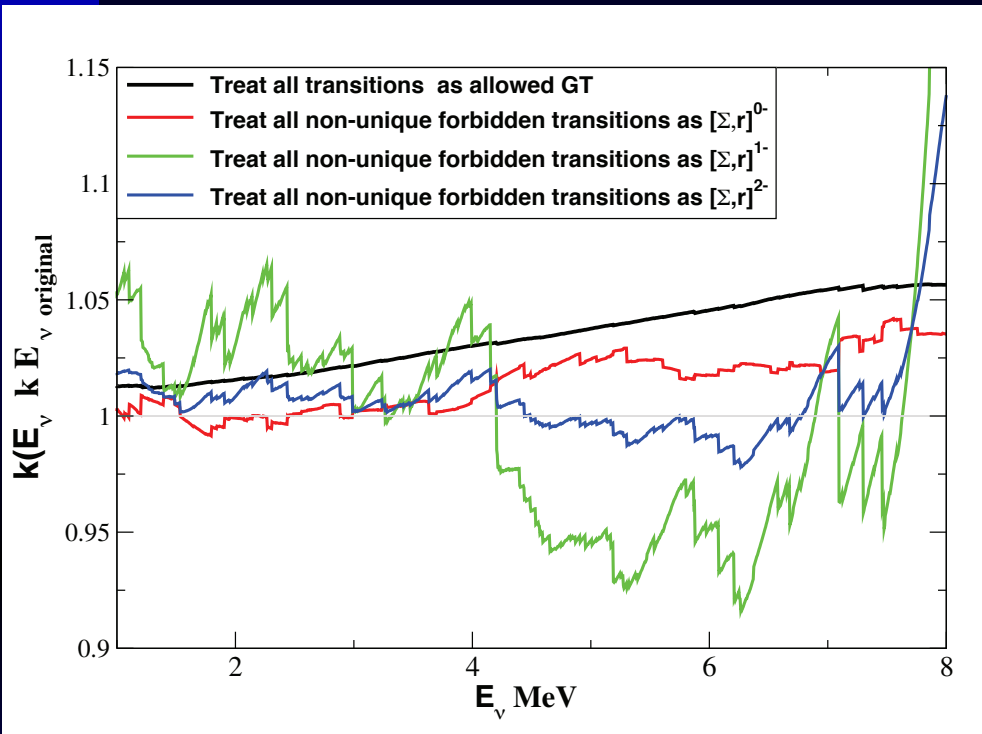
Direct summation of latest ENSDF database,
assuming allowed beta-spectrum shape

Dwyer and Langford, 2014



This direct summation, as all other direct summations, does not agree with the Schreckenbach total beta-spectrum.

Another explanation?

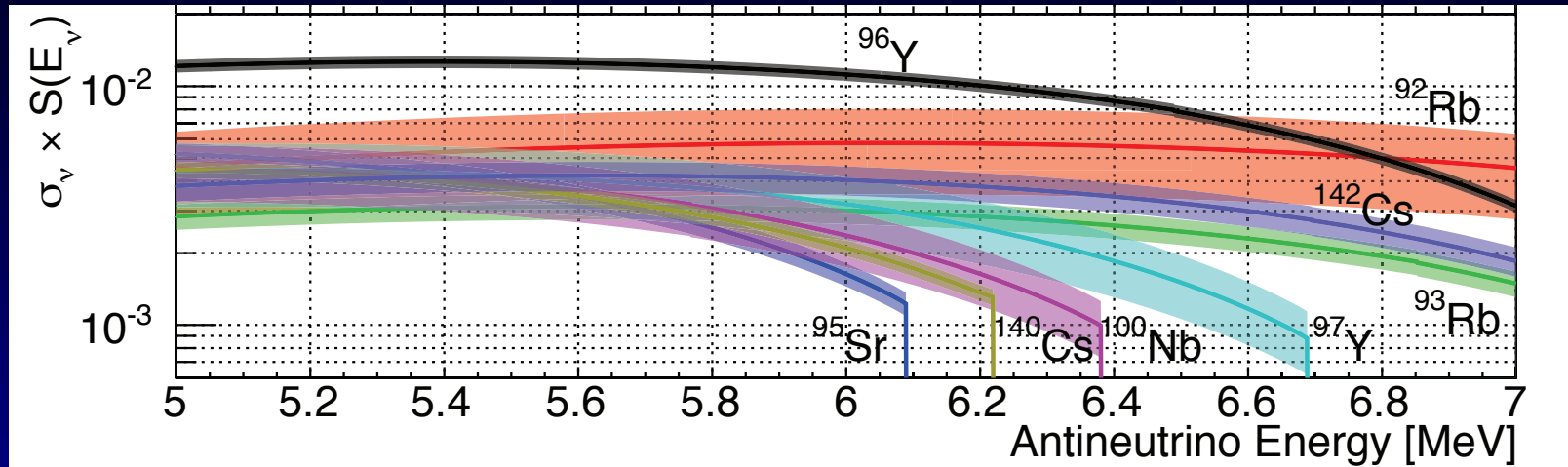


For certain operators there is a feature at 5 MeV resulting from the ensemble of all decays.

Hayes *et. al*, 2013, shown is the relative shift between beta and neutrino spectra

It has not been quantitatively shown that these forbidden decays can both reproduce the Schreckenbach data and the neutrino data.

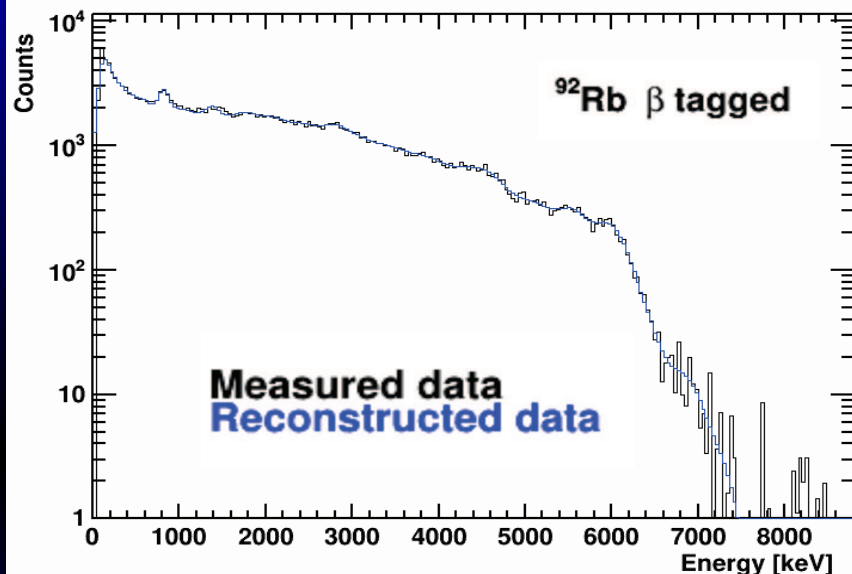
Specific isotopes



Dywer and Langford

Isotope	Q[MeV]	$t_{1/2}$ [s]	$\log(ft)$	Decay Type	N [%]	σ_N [%]	Daughter	$t_{1/2}$
^{96}Y	7.103	5.34	5.59	$0^- \rightarrow 0^+$	13.6	0.8	^{96}Zr	$> 10^{19}$ yr
^{92}Rb	8.095	4.48	5.75	$0^- \rightarrow 0^+$	7.4	2.9	^{92}Sr	2.66 h
^{142}Cs	7.308	1.68	5.59	$0^- \rightarrow 0^+$	5.0	0.7	^{142}Ba	10.6 m
^{97}Y	6.689	3.75	5.70	$1/2^- \rightarrow 1/2^+$	3.8	1.1	^{97}Zr	12.749 h
^{93}Rb	7.466	5.84	6.14	$5/2^- \rightarrow 5/2^+$	3.7	0.5	^{93}Sr	7.43 m
^{100}Nb	6.381	1.5	5.1	$1^+ \rightarrow 0^-$	3.0	0.8	^{100}Mo	$> 10^{18}$ yr
^{140}Cs	6.220	63.7	7.05	$1^- \rightarrow 0^+$	2.7	0.2	^{140}Ba	12.7527 d
^{95}Sr	6.090	23.9	6.16	$1/2^+ \rightarrow 1/2^-$	2.6	0.3	^{95}Y	10.3 m

The case of ^{92}Rb



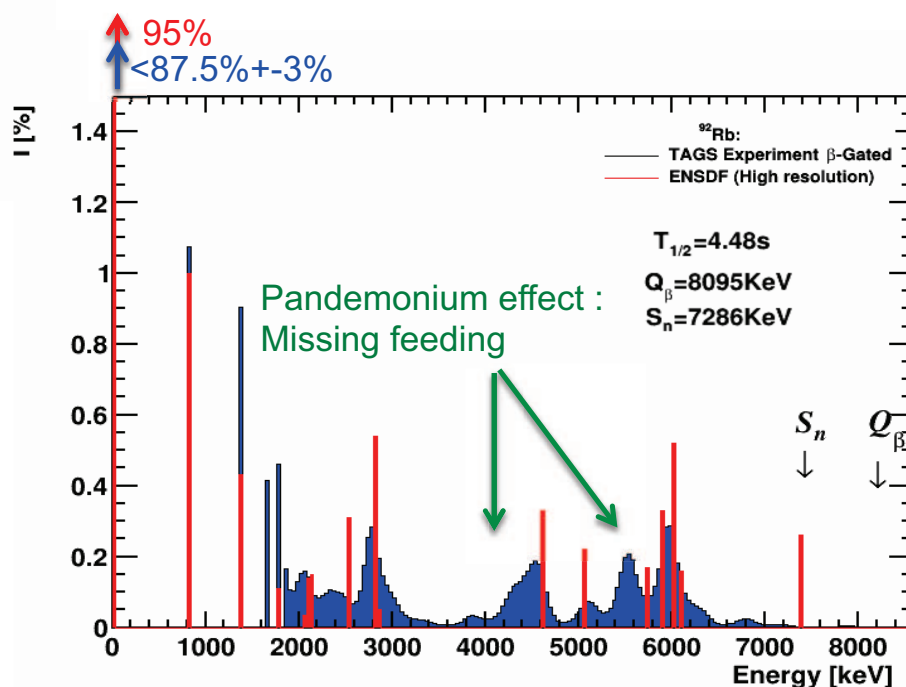
Calculation of level energy feeding through the resolution of the inverse problem

$$d_i = \sum R_{ij} * f_j$$

Clean data

Response matrix

Level feeding



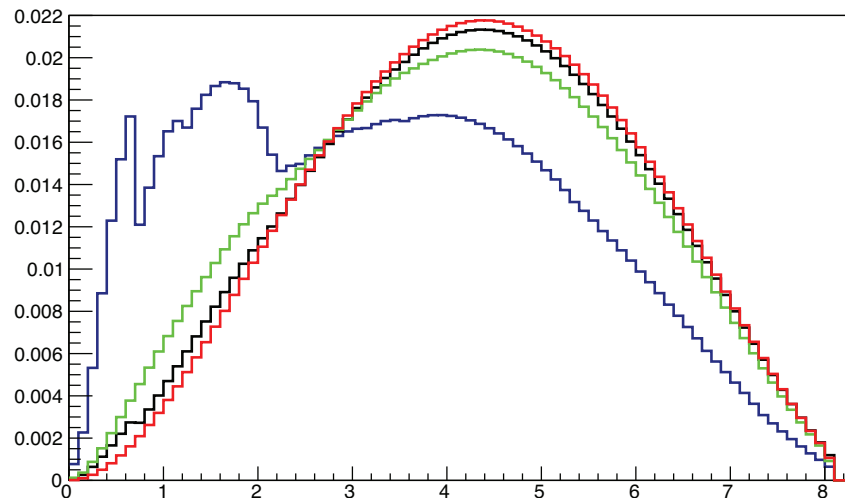
PhD Thesis work:
Zakari Issoufou (Subatech, Nantes)



Z. Issoufou et al. in preparation

Slide courtesy M. Fallot

The case of ^{92}Rb

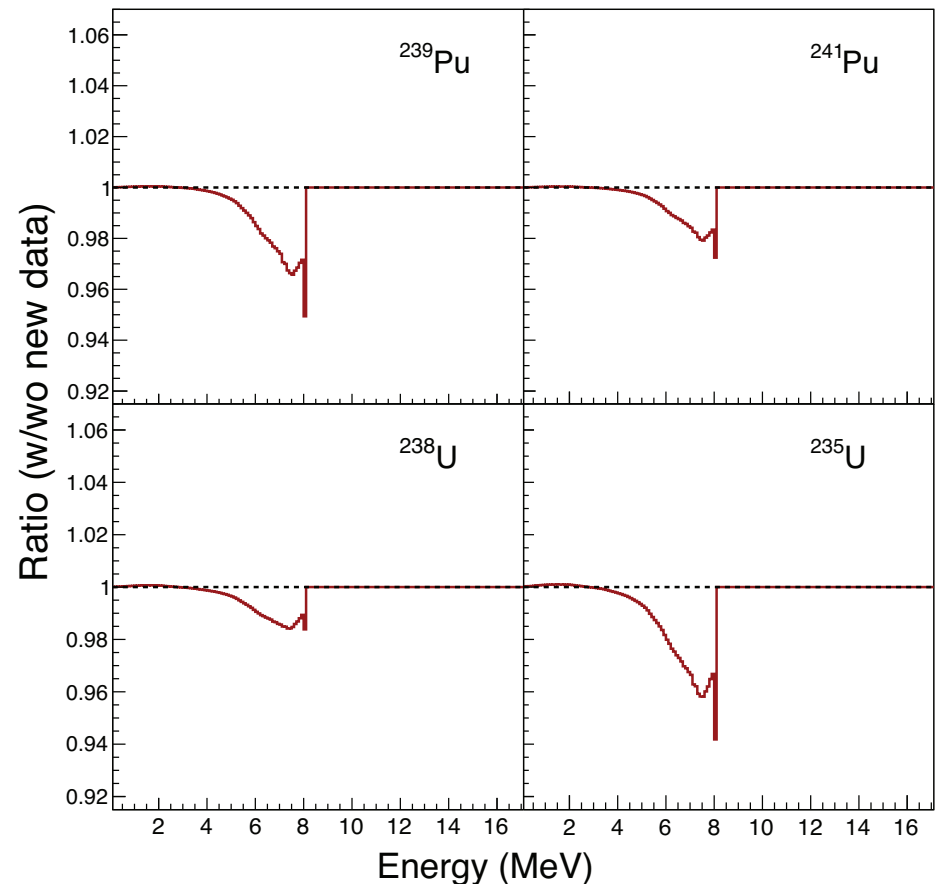


Antineutrino energy spectra:

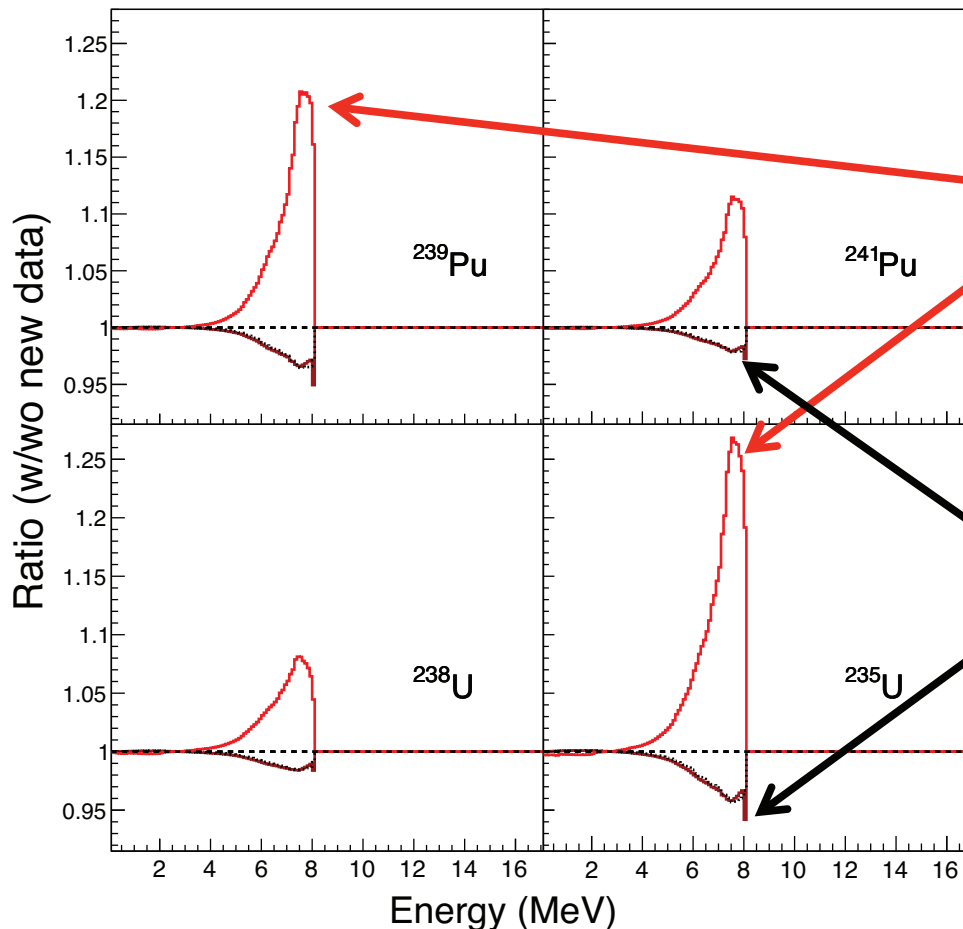
- Rudstam's data
- ENSDF before 2012
- ENSDF since 2012
- New TAS data

Ratios of summation anti-neutrino spectra including the new TAS data for ^{92}Rb over the same spectra but with the Rudstam data:

- ^{241}Pu energy spectra: reaching a 2% decrease at 7 MeV;
- ^{238}U energy spectrum: reaching a 1.5% decrease at 7 MeV;
- ^{239}Pu energy spectra: reaching a 3.5% decrease at 7 MeV;
- ^{235}U energy spectrum: reaching a 4.5% decrease at 7 MeV;



Impact on Summation Method Spectra



Z. Issoufou et al. in preparation

- Striking Change in Dwyer and Langford 's summation spectra, due to new beta decay branches of ^{92}Rb !!!

- Impact on Sonzogni 's and Fallot 's summation spectra, due to new beta decay branches of ^{92}Rb

⇒ Emphasizes why new measurements are needed for the radioactive decays of importance in the reactor antineutrino spectrum

⇒ And why the choice of nuclear data in summation spectra should be made carefully

⇒ The present measurement reduces significantly the uncertainties associated with the antineutrino summation calculations in the 4 to 8 MeV range

Slide courtesy M. Fallot

Weak magnetism

We have seen that weak magnetism, both in allowed and forbidden decays dominates the uncertainties.

CVC allows to relates the width of certain (M1) EM decays of the isobaric analog state with the size of the weak magnetism term.

Isospin violation is less than 2% even for heavy nuclei

Bertsch, Mekjian, 1972

BUT

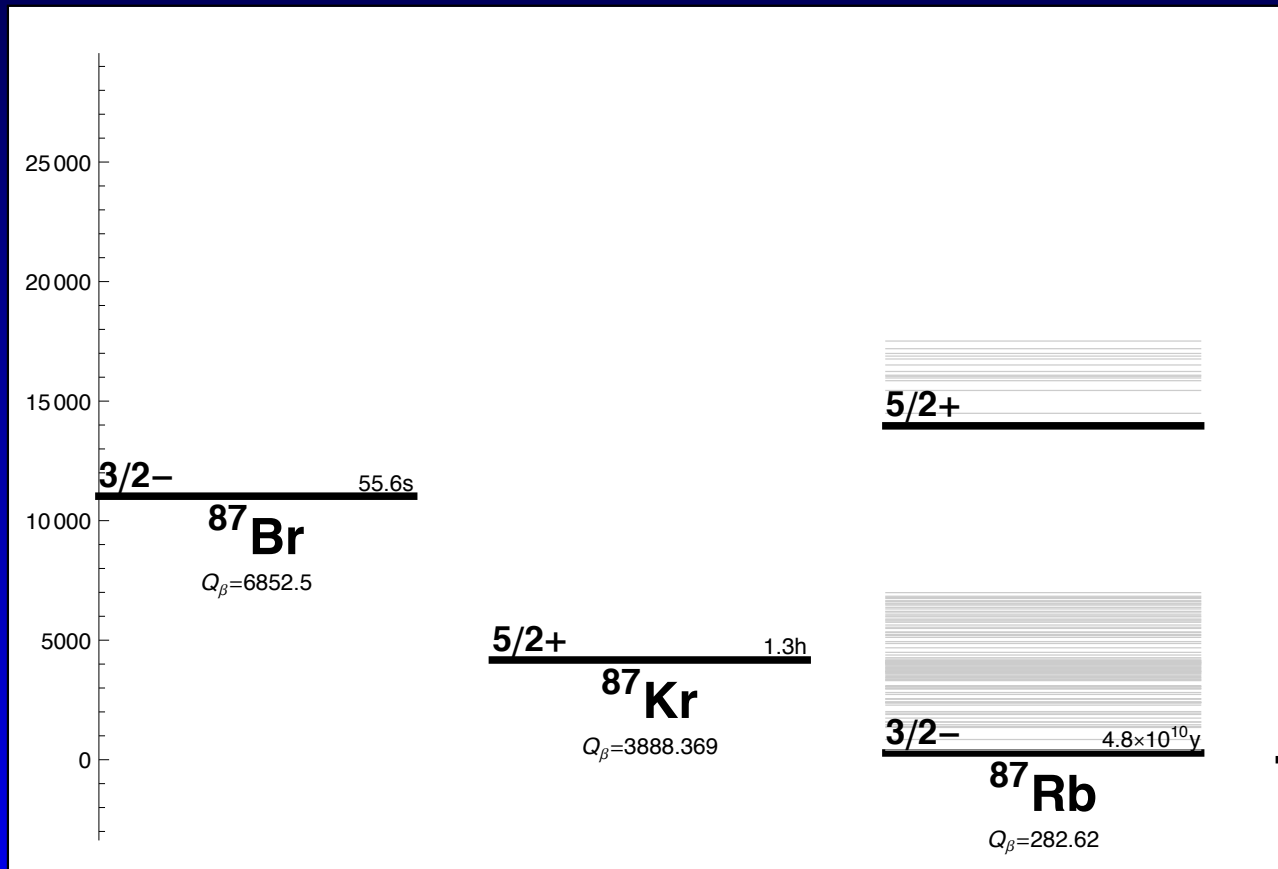
Data does not extend beyond $A=32$

Theory so far only developed for allowed decays

Example

There is significant information on isobaric analog states (IAS) through all mass.

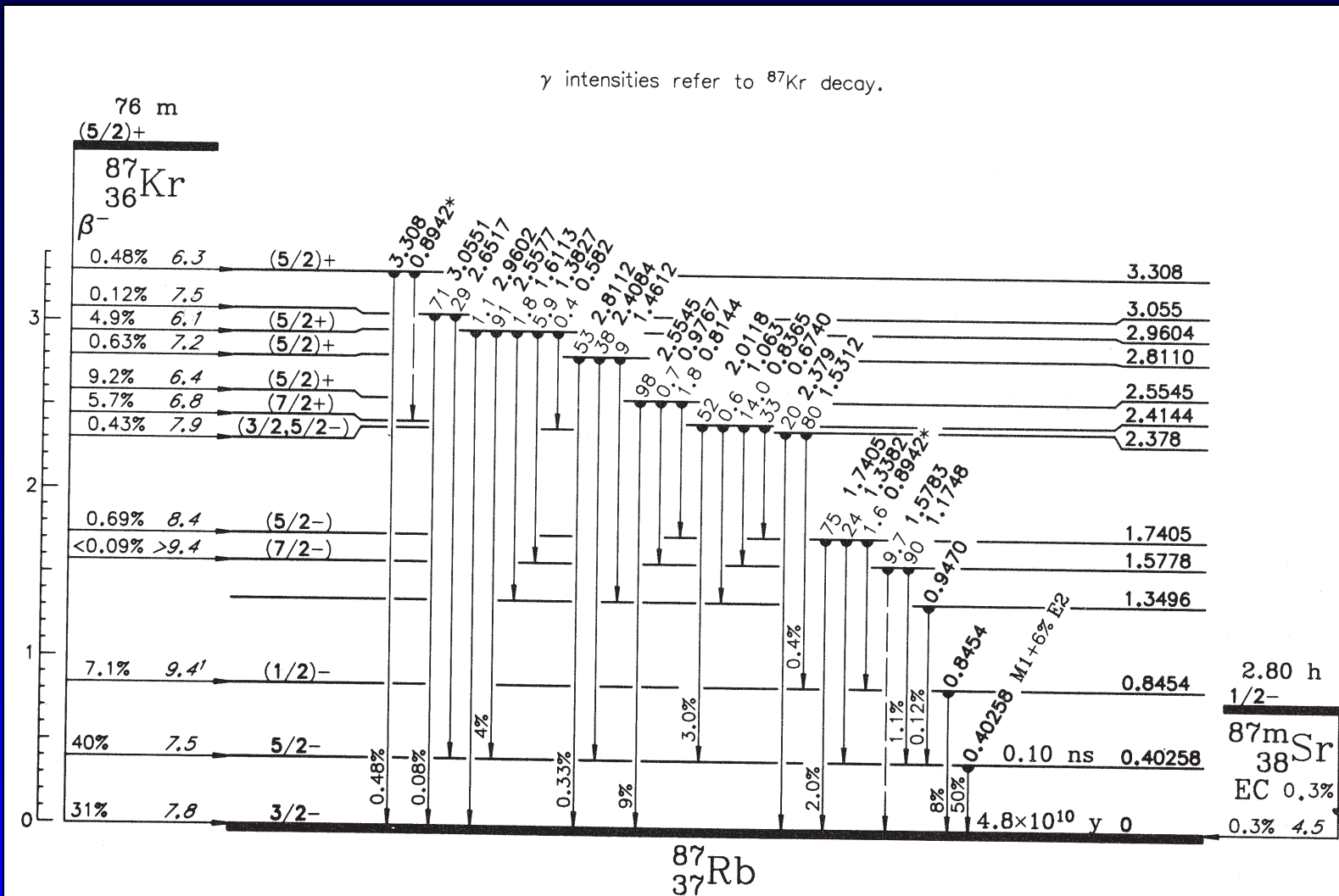
^{87}Kr , with a fission yield of about 0.5%



Ongoing experimental effort at TUNL.

But...

There are nearly no pure GS to GS allowed decays to be found, also ^{87}Kr has a complicated decay scheme



Summary

Reactors are complex neutrino sources – our current understanding is at the 2-5% level

New neutrino data will have to have systematics around 1% or better to make a real difference

The Daya Bay data set will remain a benchmark which we need to exploit to its fullest

Weak magnetism currently is our main theoretical obstacle, since it does depend on nuclear structure

Can CVC together with dedicated gamma spectroscopy solve the problem?



Questions?